

Coal-Based Power Generation Technologies

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On Energy and Air Quality

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Mr. Chairman and Members of the Subcommittee. Good morning. My name is James Katzer, and I am a Visiting Scholar in the Laboratory for Energy and the Environment of Massachusetts Institute of Technology. For about the last year, I have been working with a group of MIT faculty who have been looking at the future of coal. I am pleased to have been invited to discuss some key aspects related to this work with you today. I will focus on coal-based generation technology and certain associated environmental issues, including carbon dioxide emissions and their control. I am submitting my written testimony herewith.

Coal presents the ideal paradox in power generation. On one hand, it is cheap, abundant, and concentrated typically in countries with large human populations and limited oil and gas. On the other hand, its use can have significant environmental impacts, requires capital-intensive generating plants, and produces large quantities of carbon dioxide. Both U.S. and global electricity demand will continue to grow at a brisk rate, and coal is certain to play a major role in meeting this demand growth. As you are aware the U.S. has 27% of the total global recoverable coal reserves, enough for about 250 years at current consumption. Over 50% of U.S. electricity was generated from coal last year.

The primary technology used to generate this electricity is pulverized coal (PC) combustion. It is well-established, mature technology that generates most of the world's coal-based electricity. Although the efficiency of generation depends on a number of variables, including coal type and properties, plant location, etc., the most important efficiency determinant is the temperature and pressure of the steam cycle that is used. I will come back to this in a minute.

Integrated Gasification Combined Cycle (IGCC) is a competitor to PC generation. Four coal-based IGCC demonstration plants, each between 250 and 300 MWe, have been built, each with government assistance, and are operating well. In addition, there are about 5 refinery-based IGCC units, three at 500 MWe each, that are gasifying petroleum coke, or refinery asphalt, residua, tars, and other residues to produce electricity. These units often also produce steam and hydrogen for the refinery. IGCC is well established commercially in the refinery setting. IGCC can also be considered commercial in the coal-based electricity generation setting, but in this setting it is neither well established nor mature. As such, it is likely to undergo significant change as it matures. Currently, the biggest concern with coal-based IGCC is gasifier availability.

Because a large number of variables, including coal type and quality, location, etc, affect generating technology choice, operation, and cost, my comments here and my technology comparisons will center one point set of conditions. This includes one coal, Illinois #6 coal, a high-sulfur bituminous coal and generating plants designed to achieve criteria

emissions levels somewhat lower than the lowest recent permitted plant levels. For example, the designs that I refer to here achieve 99.4 % sulfur removal. I will first compare these technologies without carbon dioxide capture and then compare them with 90% carbon dioxide capture. Plant capital costs are based on recent detailed design studies and industrial experience of the last 6 years, which represented a relatively stable period. I have not attempted to account for recent cost escalation. Here I will focus on technologies that are either commercial or well on their way to becoming commercial.

PC Combustion: The most important variations affecting PC generating efficiency is the severity of steam cycle operation: subcritical, supercritical, and ultra-supercritical. Generating efficiency is about 35% for subcritical generation, about 38% for supercritical generation, and about 44% for ultra-supercritical generation. Increased generating efficiency means less emissions per unit of electricity, including less CO₂ emissions. In moving from subcritical to ultra-supercritical generation, the coal required per unit electricity is reduced by about 22%, which means a 22% reduction in CO₂ emissions and also reduced criteria emissions. Moving from subcritical to supercritical offers about a 10% reduction. Most PC plants in the U.S. are subcritical units. We have no ultra-supercritical plants in operation, under construction, or being planned. One reason is that low coal cost has not provided sufficient economic incentive to offset the slightly higher capital costs associated with higher steam cycle operating severity. On the other hand, Europe and Japan, which have higher coal costs and stronger culture supporting high efficiency, have built almost a dozen ultra-supercritical units over the last decade. These units are operating as well as subcritical units, but with much higher generating efficiency.

The key enabling technology here is improved materials to allow operation at higher severity conditions. An expanded U.S. program to advance materials development and particularly improved fabrication and repair technologies for these materials would advance the potential for increased PC generating efficiency for our changing future.

Another critical issue with PC generation is criteria and other emissions. Application of advanced emissions control technologies to PC units can result in extremely low emissions, and emissions control technology continues to improve, including the potential for high degrees of mercury control. In general, the issue of PC emissions is not a question of technology capability but the breadth of its application. This may not hold for specific local situations.

Using detail design study capital costs, EPRI economic TAG guidelines and assumptions and coal at \$1.50 per million Btu, the estimated cost of electricity (COE) for a subcritical PC is about 4.8 ¢/kW_e-h, consistent with recent EPRI estimates [1]. The COE decreases slightly (~0.1 ¢/kW_e-h) from subcritical to ultra-supercritical generation. For supercritical generation almost 1 ¢/kW_e-h, or about 20%, is associated with achieving emissions control to the high design levels assumed here. Reducing emissions by a factor of two further would add an estimated 0.2 ¢/kW_e-h increasing the COE to about 5.0 ¢/kW_e-h.

IGCC: The promise of IGCC has been high generating efficiency and extremely low emissions. There are a number of critical options associated with gasification technology

and its integration into the total plant that affect efficiency and operability. Of these, the gasifier type and configuration are the most important. Table 1 summarizes the characteristics of gasifier types. Entrained-flow gasifiers, which are extremely flexible, are the basis of each of the IGCC demonstration units. Figure 1 shows the configuration of an IGCC employing full quench cooling of the gasifier exit gases. This configuration will produce about 35-36 % generating efficiency. Figure 2 illustrates the addition of a radiant syngas cooler to raise steam for the steam turbine, which increases the electricity output and raises the generating efficiency to 38-39 %. Adding convective syngas coolers to recover additional heat as steam is also shown in Figure 2. It can increase the generating efficiency to the 39-40 % range. Existing IGCC demonstration units, which employ different practical combinations of these options, operate at generating efficiencies from 35.5 % (Polk) to 40.5 % (HHV) (Puertolanno Spain). Since IGCC is not yet mature, there is still potential for efficiency gain. However, I do not expect to see commercial IGCC generating efficiency exceeding that of ultra-supercritical PC in the intermediate time frame. The design/engineering firms and the power industry need to gain experience with IGCC to develop better designs and achieve improved, more reliable operation.

Current coal-based IGCC units are permitted for and are operating at the same criteria emissions levels as the best PC units. An IGCC plant with radiant and convective syngas coolers using Illinois #6 coal, operating at 38% efficiency, and achieving high levels of criteria emissions control produces electricity for about 5.1 ¢/kW_e-h or about 0.3 ¢/kW_e-h higher than a supercritical PC [1, 2]. IGCC would not be the choice based on COE

alone, independent of gasifier availability concerns. Requiring high levels of mercury removal, reducing criteria pollutants by one half from the very low levels that we are already considering and including the cost of emissions credits and offsets increases the COE for the PC, narrowing the gap, but does not suggest a shift in technology choice based on COE. However, IGCC has the potential for order-of-magnitude criteria emissions reductions, 99.5+ % levels of mercury and other toxic metals removal, much lower water consumption, and highly stabilized solid waste production. These may become a larger factor in the future. To achieve these order-of-magnitude criteria emissions reductions is expected to increase IGCC COE, but this increase is not expected to be large. Companies considering construction of a new coal-based generating facility need to bring all these considerations into their forward pricing scenarios to help frame the decision of which technology to build.

CO₂ Capture: If it becomes commercial practice, CO₂ capture will add significantly to the COE, independent of which approach is taken. CO₂ capture could also change the choice of technology in favor of IGCC, although it is too early in technology development to declare this a foregone conclusion. History teaches us that one single technology is almost never the winner in every situation. The options are:

- Capture the CO₂ from PC unit flue gas. In this case, the CO₂ is at a low concentration and very low partial pressure because of the large amount of nitrogen from the combustion air. To capture and recover the CO₂ using today's amine (MEA) technology requires a lot of energy. Energy is also required to compress the CO₂ to a supercritical liquid. This large energy

consumption reduces plant electricity output by almost 25% and reduces generating efficiency by about 9 percentage points. The added capital and the efficiency reduction increase the COE by about 60% or about 3.0 ¢/kW_e-h to about 7.7 ¢/kW_e-h. In this situation a 50% reduction in the CO₂ capture and recovery energy would have a significant impact on PC capture economics. Focused research on this issue is clearly warranted.

- Combust coal with oxygen(Oxy-fuel combustion) to reduce the amount of nitrogen in the flue gas. This allows the flue gas to be compressed directly liquefying the CO₂ without a costly separation step first, significantly reducing the energy consumption. The technology required the addition of an air separation unit which consumes significant energy and thus would not be used except for CO₂ capture. This technology is in early development stage, is advancing well, and at this point appears to hold significant potential for both new-build capture plants and for the retrofitting existing PC plants. The estimated COE for oxy-fuel combustion is about 7.0 ¢/kW_e-h (includes capture and compression to supercritical liquid, but not transport of sequestration) or about 0.7 ¢/kW_e-h less than for air-blown PC combustion with capture. The technology requires further development and demonstration along with detailed design studies to allow effective evaluation of its cost and commercial potential.
- Use IGCC, shift the syngas to hydrogen, and capture the CO₂ before combustion in the gas turbine. IGCC should give the lowest COE increase for CO₂ capture because the CO₂ is at high concentration and high partial pressure,

and this is what is observed. The needed technology is all commercial, although it has never been fully integrated on the scale that it will need to be applied here. The estimated COE is 6.5 ¢/kW_e-h [1] which is a 1.4 ¢/kW_e-h increase over non-capture IGCC and is about about 1.2 ¢/kW_e-h less than supercritical PC with capture. Oxy-fuel combustion falls in between them

Lower Rank Coals: As Figure 3 shows, moving from bituminous coal to sub-bituminous coal and to lignite results in an increase in the capital cost for a PC plant and a decrease the generating efficiency (increased heat rate). However, for IGCC, these trends are much larger, such that currently demonstrated IGCC technologies become more substantially disadvantaged relative to PC for subbituminous coals and lignite. Note that over half of the U.S. recoverable coal reserve is either subbituminous coal or lignite. Thus, there is a substantial need for improved IGCC technology performance on lignite, other low rank coals, and biomass. Options include, but are not limited to, improved dry-feed injection into the gasifier, coal drying, fluid transport reactors and other gasifier configurations. Development should be at the PDU scale before moving to demonstration.

A variation on PC combustion is fluid-bed combustion in which coal is burned with air in a fluid bed, typically a circulating fluid bed (CFB)[2, 3] CFBs are best suited to low-cost waste fuels and low-rank coals. Crushed coal and limestone are fed into the bed, where the limestone undergoes calcination to produce lime (CaO) which captures sulfur. The steam cycle and generating efficiencies are similar to PC. The primary advantage of CFB technology is its capability to capture SO₂ in the bed, and its flexibility to a wide

range of coal properties, including low-rank coals, high-ash coals and low-volatile coals. The technology is fully commercial, and several large new lignite-burning CFB units have been constructed recently. CFBs are well suited to co-firing biomass [4].

When CO₂ capture is considered, the differences among IGCC, oxy-fuel PC and air-blown PC become significantly less than discussed above for bituminous coal.. In this situation all three of the technologies with CO₂ capture must be considered to be in the early stages of development, and it is simply too early to select one of these technologies as the winner vs. the others

Key Findings:

- PC technology, although mature, still offers opportunities for improved efficiency and thus reduced coal consumption and CO₂ emission per unit of electricity generated. Higher efficiency generation is important without CO₂ capture but also makes CO₂ capture less costly. An expanded program to develop and apply new materials for more severe steam cycle operation is warranted.
- PC emissions control technology has become very effective in reducing criteria emissions, but it continues to expand its capabilities. The limit of the technology has not yet been reached although increases in extent of required removal and addition of new requirements continue to increase the PC COE.
- IGCC is commercially demonstrated technology that is not yet mature in the power generation arena, although it is mature in the refinery arena. With coal its main challenges are gasifier availability and COE. It has the potential of a much smaller environmental footprint than PC technology and of markedly lower air

emissions. In the near term, these advantages do not drive a change in generating technology.

- Current commercial IGCC technology is not well suited for lower rank coals, of which the U.S. has a large amount. To expand its potential scope to these coals, IGCC technology needs to undergo further targeted development.
- The technology systems required to capture CO₂ from coal-based power production are in the early stages of development. Of the three competing systems (PC with CO₂ recovery from flue gas, Oxy-fuel combustion with flue gas direct compression to liquefy CO₂, and IGCC with pre-combustion CO₂ capture) it is too early to choose winners because it is not possible to predict how technology development and commercial innovation may evolve. Further, one technology system may be well suited for bituminous coals, whereas another may apply best to low rank coals and lignite..

Citations and Notes

1. Dalton, S., *The Future of Coal Generation*, in *EEI Energy Supply Executive Advisory Committee*. 2004.
2. NCC, *Opportunities to Expedite the Construction of New Coal-Based Power Plants*. 2004, National Coal Council.
3. Beer, J.M. *The Fluidized Combustion of Coal*. in *XVIth Symposium (Int'l) on Combustion*. 1976. MIT, Cambridge: The Combustion Institute, Pittsburgh.
4. Combustion-Engineering. *Fluid Bed Combustion Technology for Lignite*. 2005

Table 1. Characteristics of different gasifier types

| | Moving bed* | Fluid bed** | Entrained flow*** |
|------------------------|--|---------------------------|-------------------------------------|
| Outlet temperature | Low (425-600 °C) | Moderate (900-1050 °C) | High (1250-1600 °C) |
| Oxygen demand | Low | Moderate | High |
| Ash conditions | Dry ash or slagging | Dry ash or agglomerating | Slagging |
| Size of coal feed | 6-50 mm | 6-10 mm | < 100 µm |
| Acceptability of fines | Limited | Good | Unlimited |
| Other characteristics | Methane, tars and oils present in syngas | Low carbon conversion | Pure syngas, high carbon conversion |

* Lurgi is an example

** KBR transport reactor, BHEL, KRW are examples

*** GE, E-Gas, Shell are examples

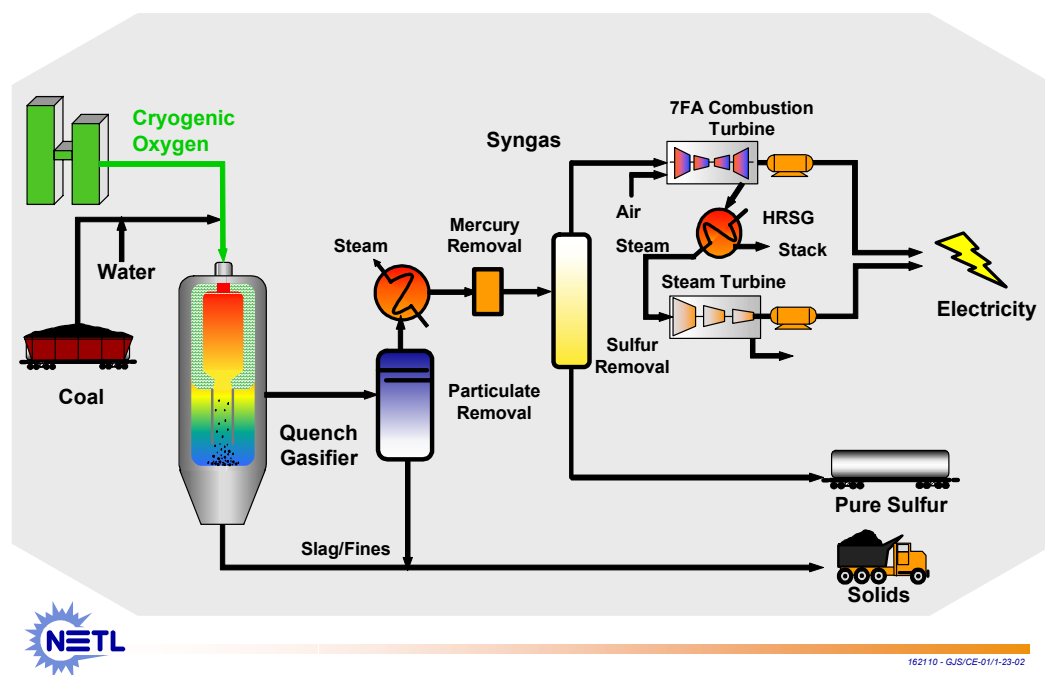


Figure 1. IGCC Plant with Entrained Flow (GE) Full Quench Gasifier

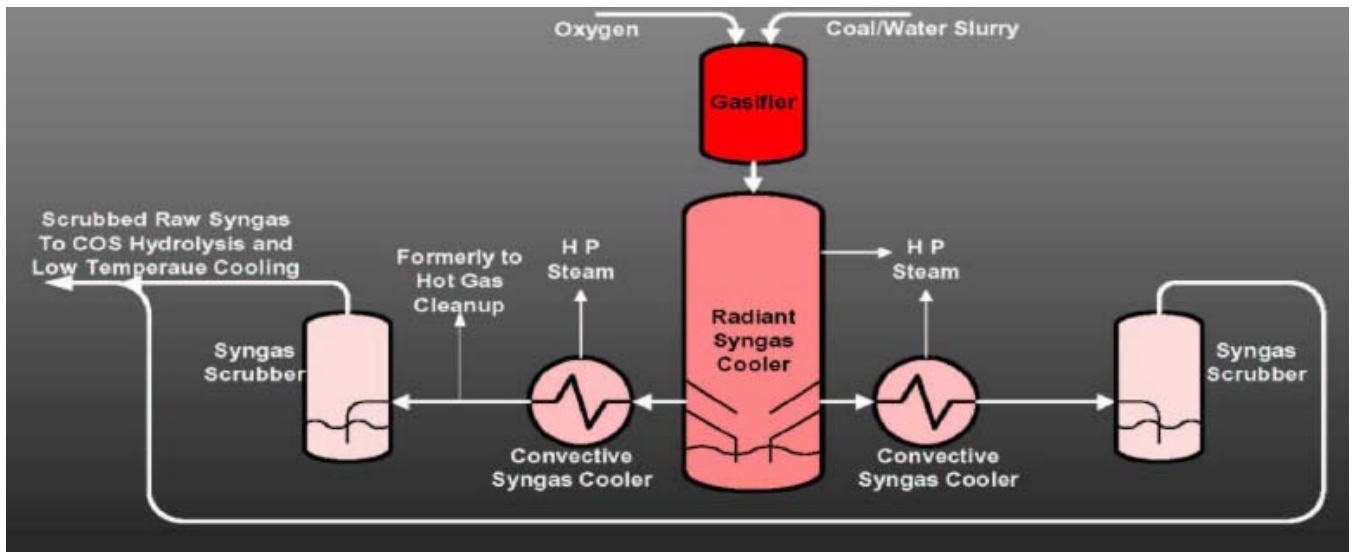


Figure 2. Heat Recovery Options for Entrained-Flow Gasifier

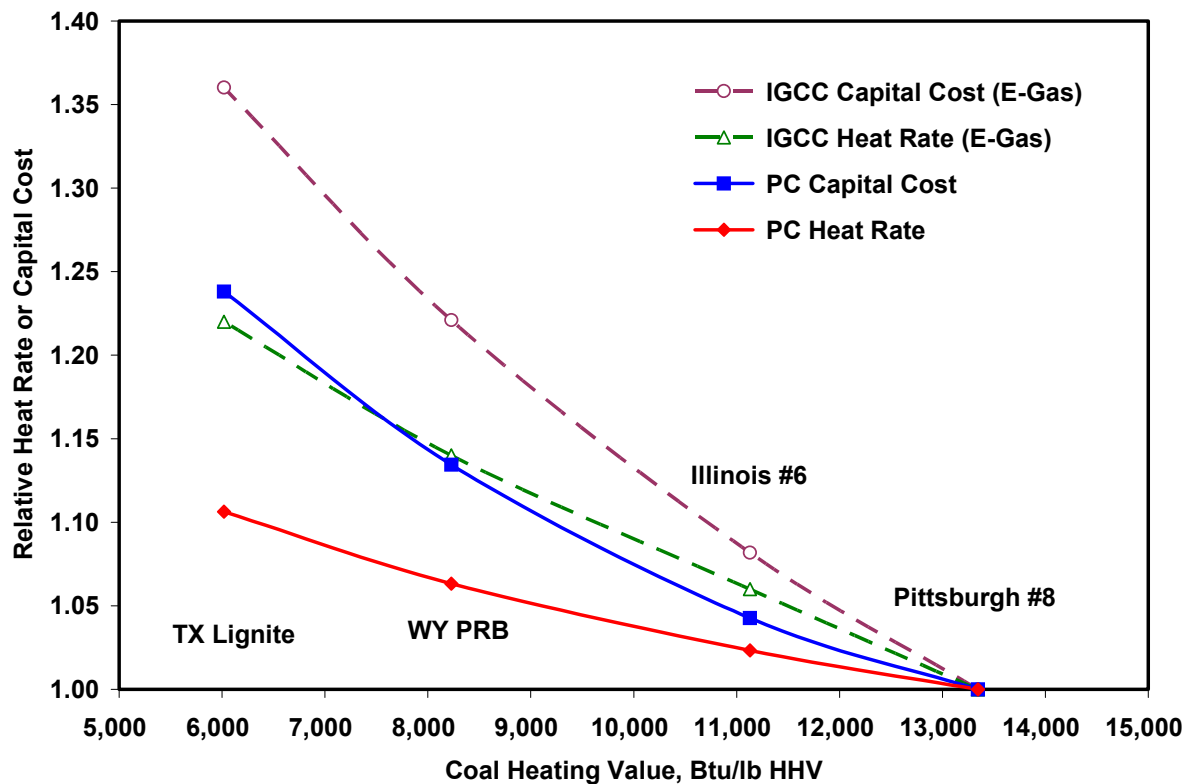


Figure 3 Effect of Coal Type (Rank) on Capital Cost and Heat Rate for PC and IGCC